

Design and Modeling of Silicon MEMS Accelerometer

Meftah Hrairi, Badrul Hanafi bin Baharom

Mechanical Engineering Department
International Islamic University Malaysia
meftah@iium.edu.my

Abstract— In developing Micro Electro Mechanical Systems (MEMS), Finite Element Analysis (FEA) is usually relied upon to study these micro-structures in determining stress, deformation, resonance, temperature distribution, electromagnetic interference, and electrical properties. With this kind of approach, the performance of the devices can be easily expanded, as well as reducing the time and cost of MEMS production. This paper focuses on the modeling of silicon MEMS accelerometer in an attempt to design a surface micro-machined accelerometer that satisfies certain pre-determined specifications.

Keywords—component; MEMS; FEA; accelerometer; design; modeling

I. INTRODUCTION

Nowadays, there is a huge interest in Micro Electro Mechanical Systems (MEMS) technology. This industry has been established in recent years and has generated a rapid introduction of new products in various applications such as automotive, biochemical analysis, communication, etc. MEMS promises to revolutionize nearly every product category by bringing together silicon-based microelectronics with micromachining technology, making possible the realization of complete systems-on-a-chip. It is an enabling technology allowing the development of smart products, augmenting the computational ability of microelectronics with the perception and control capabilities of microsensors and microactuators and expanding the space of possible designs and applications [1]. Hence, it is important to continuously develop MEMS technology so that it will give a lot of benefits especially in the automotive industry.

The usage of Finite Element Analysis (FEA) in the MEMS industry cannot be denied since it is already acknowledged as the best way to optimize the performance of MEMS devices [2]. Modern simulation tools are also becoming more frequently used for MEMS devices. Instead of constructing the MEMS devices in the laboratory, the simulation of MEMS using FEA programs like ANSYS, ABAQUS, LS-DYNA, etc. has many advantages in terms of time, and cost. The simulation of the device can be repeated continuously until the desired result is achieved. Moreover, it can be used in almost every engineering discipline. Once the process is completely done, the data is used to build the device in laboratory.

Micro-accelerometers or accelerometers are one of the most important types of MEMS device, which have the second largest sales volume after pressure sensors [3]. The large volume demand for MEMS accelerometers are due to their capability to be used in many applications especially automotive industry. They can be used to measure tilt, motion, position, vibration, and shock.

Generally, an accelerometer consists of either a proof mass, seismic mass, or comb finger suspended by compliant beams anchored to a fixed frame. The operation can be modeled by a second-order mass-damper-spring system. External acceleration can be measured by relative displacement (capacitance) or by suspension-beam stress (piezoresistive).

This paper focuses on the modeling of a silicon MEMS accelerometer in an attempt to design a surface micro-machined accelerometer that satisfies certain pre-determined specifications.

II. DESCRIPTION OF THE ACCELEROMETER

In the case of a MEMS accelerometer, significantly different arrangements are made because of the very limited space available in micro-devices. A silicon beam with an attached mass constitutes a spring mass system. The air in the surrounding space is used to produce the damping effect. The structure that supports the mass acts as a spring. Most MEMS accelerometers are built on the principles of mechanical vibration.

The accelerometer consists of a silicon mass that is suspended by a spring. Acceleration will cause a force to act on the mass, which is consequently deflected by a distance x (Fig. 1). The measurement of acceleration relies on Newton's classical law. Hence, the equation of motion for the mass, m , is given by

$$m \ddot{x} + \beta \dot{x} + k x = ma \quad (1)$$

where β and k are the damping coefficient and the spring constant, respectively. Thus, the acceleration, a , can be determined by measuring the net stretch or compression of the spring.

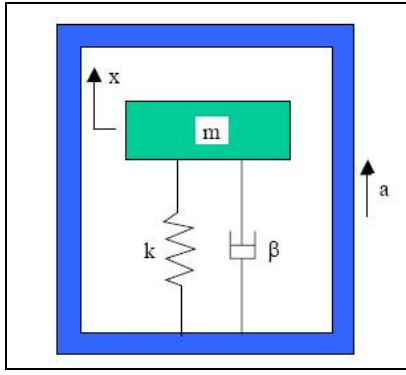


Figure 1. Accelerometer sensing principle

The MEMS accelerometer has a configuration as shown in Fig. 2. The silicon mass is suspended by eight beams which are also fabricated from silicon. A piezoresistor is implanted on the beam to measure the deformation of the attached mass, from which the amplitudes, and thus the acceleration, of the vibrating mass can be correlated. By using micromachining technology, the silicon mass is shaped like a truncated pyramid (Fig. 3).

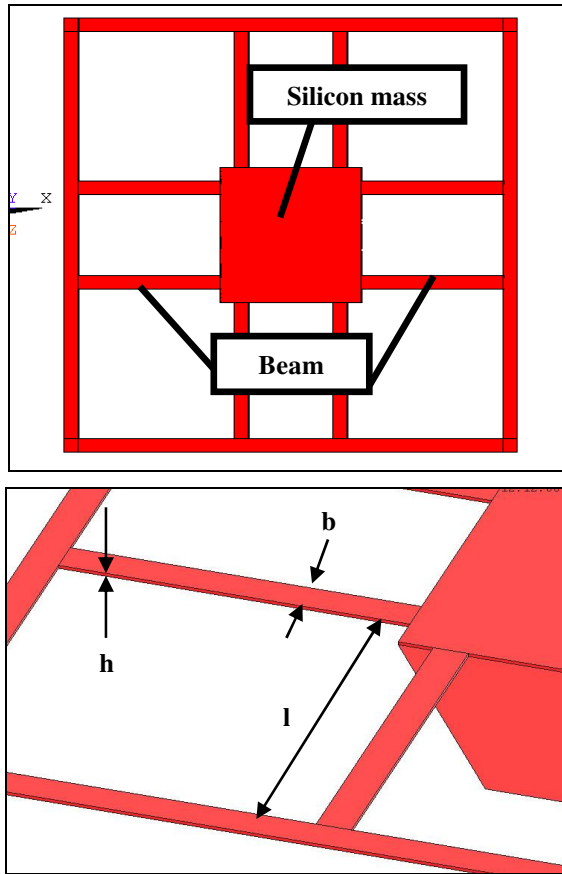


Figure 2. A schematic of the microaccelerometer

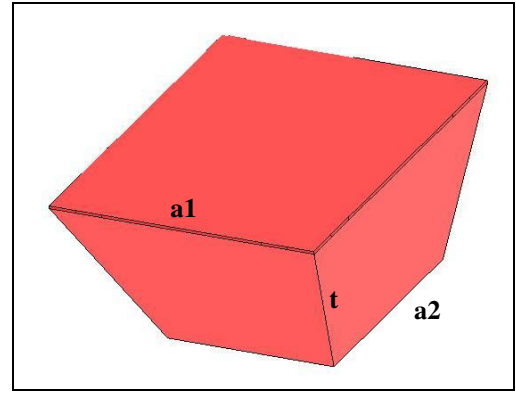


Figure 3. 3-D view of the silicon mass in the accelerometer

III. ACCELEROMETER DESIGN PROCEDURE

In general, for the design of a MEMS device with moving parts, the analysis usually starts with a structural analysis and a vibration analysis. This work focuses on the modeling of the silicon MEMS accelerometer only, which attempts to design a surface micro-machined accelerometer that satisfies the specifications in Table I [4].

TABLE I. ACCELEROMETER SPECIFICATIONS

Parameter	Design value
Bandwidth, ω_c	Greater than 4 kHz
Acceleration, a	Smaller than 0.02g
Damping ratio, ξ	$0.6 < \xi < 1.1$
Resonant frequency, f_r	Greater than 1 kHz
Shock resistance	1g

Some of the range of parameter geometries used in the design are fixed and cannot be changed due to limitation of existing technology. Therefore, the physical design is restricted by this factor. These parameters are listed in Table II [4].

TABLE II. CONSTRAINTS ON IMPORTANT PARAMETERS OF THE ACCELEROMETER OPERATION

Parameter	Design value
Height of the beam, h	$2 \leq h \leq 10 \mu\text{m}$
Width of the beam, b	$100 \leq b \leq 300 \mu\text{m}$
Length of the beam, l	$300 \leq l \leq 600 \text{ mm}$
Length of upper part of silicon mass, a_1	$1 \leq a_1 \leq 5 \mu\text{m}$
Depth of air gap between silicon mass and bottom encapsulation, d	$5 \leq d \leq 40 \mu\text{m}$

The accelerometer is designed for single axis acceleration detection. Without any external mechanical element, the displacement of the silicon mass attached to the beam will be

zero. The design of the accelerometer involves the selection of parameters which are the dimension of silicon mass (a_1), the dimension of the silicon beams (l , b , and h) and the depth (d) of the air gap between the silicon mass and the bottom encapsulation. All the calculated dimensions must satisfy the bandwidth, acceleration, damping ratio, and resonant frequency specifications. The micro accelerometer design is to be accomplished by exploring the design parameter space using the following design procedure:

A. Characteristics of the silicon mass

The mass, m , of the truncated-pyramid silicon depends on its geometry

$$m = \frac{\rho t(a_1^3 - a_2^3)}{3(a_1 - a_2)} \quad (1)$$

where $\rho = 2300 \text{ kg/m}^3$ is the density of silicon, $t = 525 \text{ }\mu\text{m}$ is the thickness of the silicon mass, and $a_2 = a_1 - t/\sqrt{2}$

B. Spring constant

The stiffness constant k , which is an important intermediate parameter in the determination of natural frequency, depends on the geometry of the silicon beam and on Young's modulus of the material. Since the silicon mass is suspended by eight beams, the spring constant is given by

$$k = \frac{8Ebh^3}{l^3} \quad (2)$$

C. Damping coefficient

The damping coefficient, β , has a significant effect on the physical behavior of a mechanical vibration system. The damping force arises from the squeeze-film effect, which is the interaction of the silicon mass and the air film, trapped in the gap between the mass and the bottom encapsulation

$$\beta = \frac{0.42\mu a_2^4}{d^3} \quad (3)$$

where μ is the dynamic viscosity of air.

D. Natural frequency

Natural frequency, ω_n , is defined as the frequency of the free vibration of a system. It depends on the stiffness constant, k , and the mass of the silicon, m

$$\omega_n = \sqrt{\frac{k}{m}} \quad (4)$$

E. Damping ratio

This is the ratio of the actual damping coefficient to the critical damping coefficient. It depends on the damping coefficient, the silicon mass, and the stiffness constant

$$\xi = \frac{\beta}{\sqrt{4mk}} \quad (5)$$

F. Minimum measurable spring deflection

By making the applied acceleration a constant, the steady net stretch or compression of the spring is directly proportional to the applied acceleration. If the minimum measurable spring deflection is $l\epsilon_{\min}$, then the minimum measurable spring deflection, a_{\min} , can be calculated by

$$a_{\min} = l\epsilon_{\min}\omega_n^2 \quad (6)$$

where $\epsilon_{\min} = 5 \times 10^{-7}$ is the minimum measurable strain of the silicon beams.

G. Bandwidth

The bandwidth of the system, ω_c , is given by

$$\omega_c = Y\omega_n \quad (7)$$

where $Y = \sqrt{1 - 2\xi^2 + \sqrt{(1 - 2\xi^2)^2 + 1}}$

Table III displays all the accelerometer geometry characteristics that have been determined following a parametric study using an Excel file.

TABLE III. SELECTED GEOMETRICAL CHARACTERISTICS OF THE ACCELEROMETER

Parameter	Design value
Height of the beam, h	4 μm
Width of the beam, b	210 μm
Length of the beam, l	410 μm
Length of upper part of silicon mass, a_1	2 mm
Depth of air gap between silicon mass and bottom encapsulation, d	34 μm

To check whether the selected parameters are acceptable, they were put into the above derived equations and the following results were obtained: $a = 0.0023\text{g}$, $\omega_c = 9.6 \text{ kHz}$, $\xi = 0.62$. All these values are found to be within the required design specifications.

IV. FINITE ELEMENT MODELING

Since the silicon mass is symmetrically suspended by the beams, it can be modeled as shown in Fig. 4 where axisymmetric solid elements with 8 nodes (PLANE82) have been used to mesh the structure. The values of silicon's Young's modulus, Poisson's ratio, and density used in the simulation are defined as 190 GPa, 0.29 and 2300 kg/m³, respectively. The linear thermal expansion coefficient is set to 2.33×10^{-6} 1/°C to investigate the effect of temperature on the accelerometer behavior. An inertia load is applied in the y-axis.

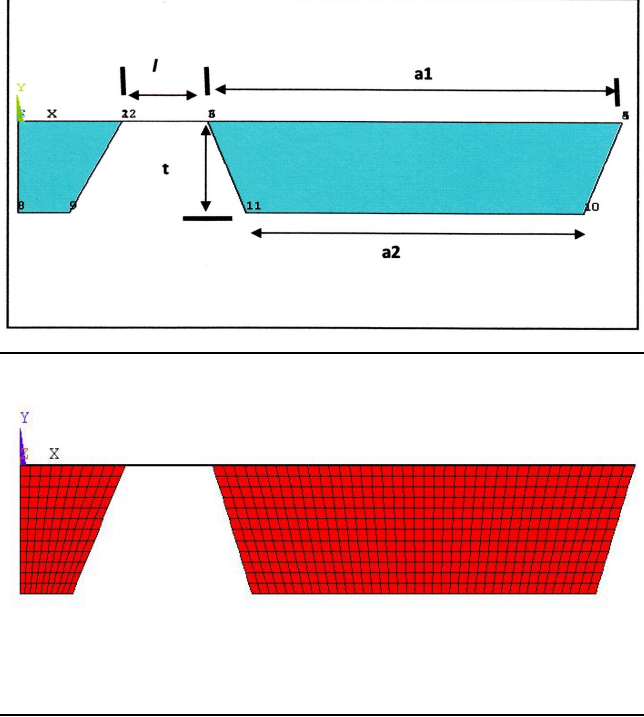


Figure 4. Geometric modeling and meshing of the accelerometer

A. Simulated displacement results

In the current simulation, the accelerometer is designed for single axis acceleration detection (y-axis). Without any external mechanical loading, the displacement of the silicon mass will be zero. When an inertia load of 0.0015g is applied to the accelerometer, silicon mass deforms in y-axis direction. The displacement results are displayed in Fig. 5.

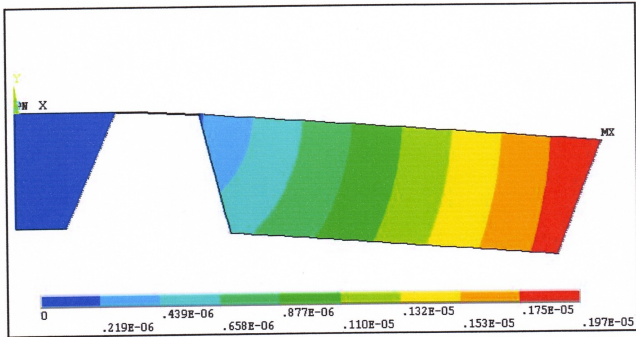


Figure 5. Displacement contours due to 0.0015g acceleration.

The analytical value of the maximum displacement, simply calculated from Newton's law, is 0.2×10^{-5} mm. However, as depicted in Fig. 5, the maximum displacement of the accelerometer is 0.197×10^{-5} mm leading to an error of 1.5% between the analytical and the FEA numerical values.

B. Simulated stress results

Besides the study of displacement, the stress supported by the accelerometer due to acceleration was also investigated. This will help determine the maximum inertia load that the device can withstand before it fails by yielding. From Fig. 6, the maximum stress of 0.017044 GPa, that occurs at the beam for a 0.0015 g acceleration load, is still below the yield strength of silicon (7 GPa).

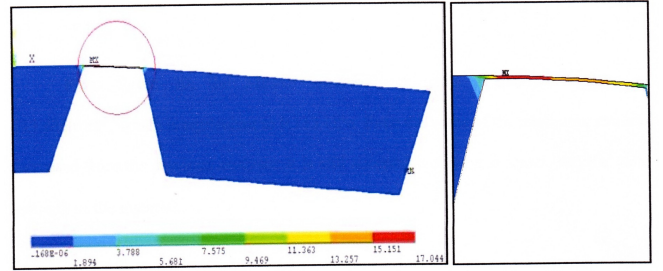


Figure 6. Von Mises stress distribution for 0.0015g acceleration

Per the required specifications stated in Table I, the accelerometer should be able to withstand the stress caused by a maximum acceleration value of 0.01 g. Fig. 7 shows that the maximum stress reaches the value of 0.113 GPa which is still acceptable since it is less than the yield stress of the material.

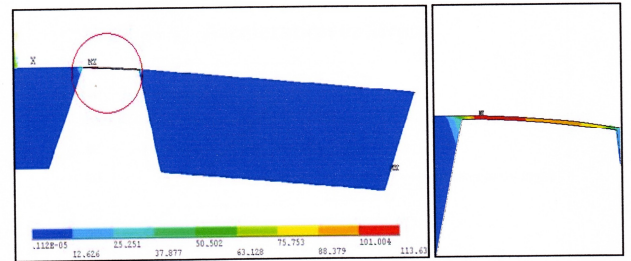


Figure 7. Von Mises stress distribution for 0.01g acceleration

C. Accelerometer measurement range simulation

From the results obtained using the loads of both Fig. 6 and 7 as well as for other loads, the relationship between the stress and acceleration can be correlated as shown in Fig. 8. The latter shows the simulation results of the relationship between the media acceleration and the maximum stress. In addition to the usual linear dependency between the maximum stress (and consequently the sensor output) and the applied acceleration, this graph can be used to determine when the applied pressure causes the maximum stress on silicon to reach the yield strength, the acceleration value is the upper limit of the sensor measurement range. For the accelerometer under study, a maximum acceleration of 0.62g will cause the membrane material to yield.

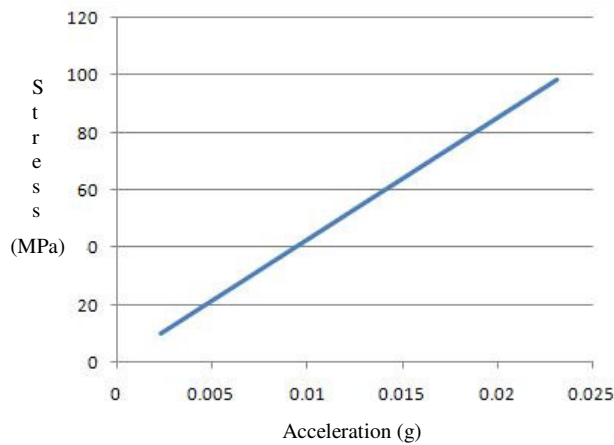


Figure 8. Acceleration – stress relationship

D. Effect of temperature on displacement

The temperature test is done to study the effect of temperature on the displacement of the accelerometer. Temperature loads of 10°C and 50°C are applied to the accelerometer. This test is particularly important for the MEMS accelerometer used to measure engine knock or vibration. From Fig. 9 and 10, it can be seen that the displacement increases when the temperature increases. However, the value of displacement is very small, confirming the fact that one of the reasons that silicon is widely used in MEMS technology is because it has a low thermal expansion coefficient.

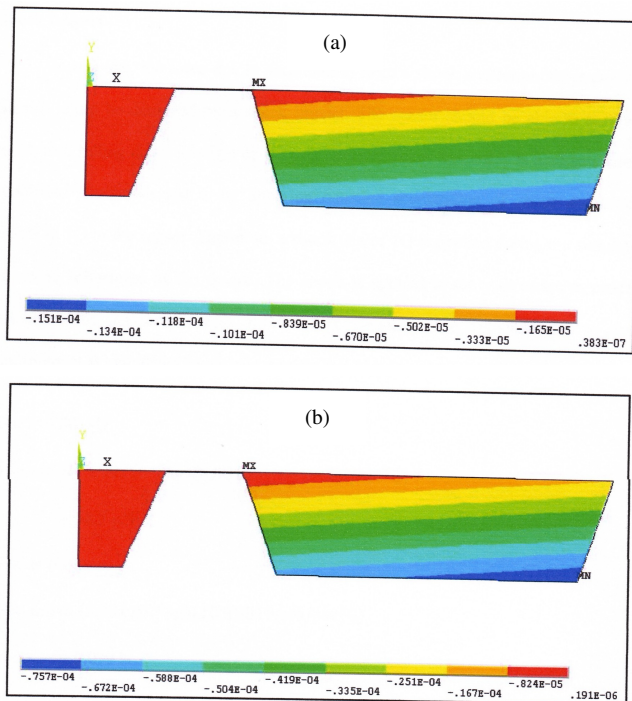


Figure 9. Effect of temperature on displacement (a) 10°C (b) 50°C

V. CONCLUSION

It has been shown that Finite Element Simulation of MEMS is very important and valuable in determining and optimizing device characteristics, and is thus valuable in the industry. Using the FEA software ANSYS, many modeling tasks in MEMS can be implemented easily. Additionally, their performance can also be determined so that it satisfies the needs of various fields. A complete finite element simulation method for an accelerometer has been carried out. By using this model, a variety of accelerometers with different measurement ranges and cavity depth can be designed.

Furthermore, temperature between 10°C to 50°C was applied to the accelerometer to check whether an increase in temperature had an impact on the displacement. For this simulation, the distribution of temperature was uniform in the MEMS accelerometer. From the simulation, it can be seen that the displacement is increased when the temperature is increased. However, the value of displacement is very small.

ACKNOWLEDGMENT

The authors would like to thank Lynn Mason for her help in editing this paper.

REFERENCES

- [1] B. S. Sreeja and S. Radha, "Design and implementation of MEMS based differential voltage controlled oscillator", In Proceedings of EIT'2009, Windsor, Canada, 2009, pp.202-206.
- [2] N. Yazdi, F. Ayazi, and K. Najafi, "Micromachined inertial sensors", in IEEE Proceedings, vol 86, no 8, 1998, pp. 1640–1659.
- [3] B. Liu, Q. Yao and B. Kriegbaum, "Finite element based design and optimization for piezoelectric accelerometers", Proceedings of Inter-Noise 98, Christchurch, New Zealand, 1998.
- [4] K. H. Denishev, and M. R. Petrova, "Accelerometer design", In Proceedings of ELECTRONICS'2007, 2007, pp. 159-164.